Extracting, Tracking, and Visualizing Magnetic Flux Vortices in Complex-Valued Superconductor Simulation Data

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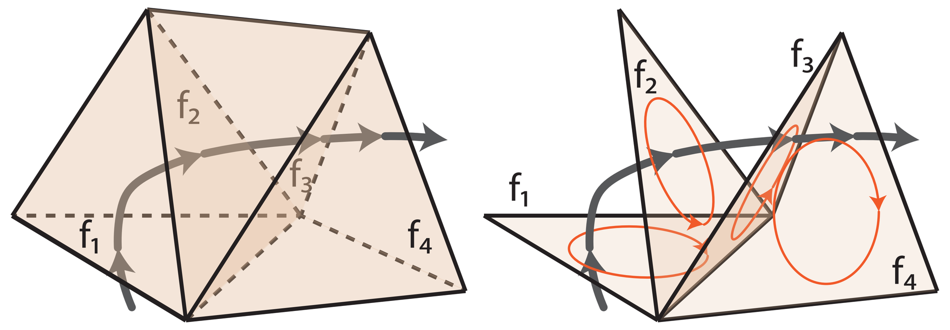
Vortices in TDGL Simulation Data

In Ginzburg-Landau theory of superconductivity, vortex lines are defined as the locus of singularity points in the complex-valued order parameter field ψ, which satisfy

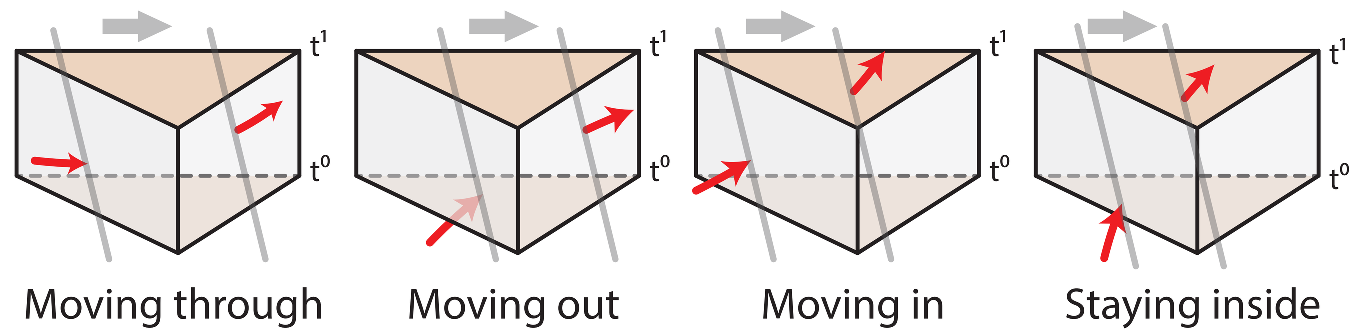
$$|\psi|=0 \quad \text{and} \quad -\oint_C \nabla\theta\cdot d\mathbf{l} = 2n\pi.$$

Extracting, tracking, and visualizing vortices in large scale time-dependent Ginzburg-Landau (TDGL) simulation data are needed to understand the dissipative material behaviors and the impact of adding inclusions.

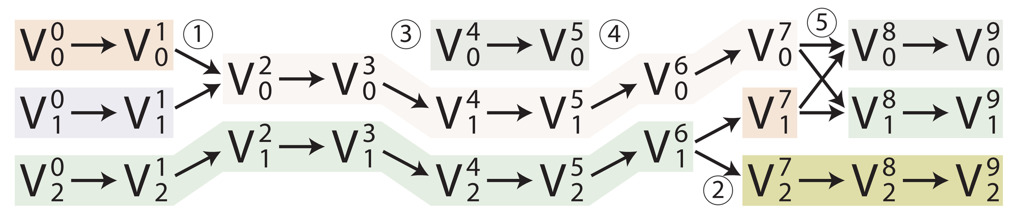
Vortex Extraction and Tracking



In a single time frame, singularities are localized by checking phase jumps over mesh faces. As there are always equal numbers of "ins" and "outs" for each cell, the punctured faces are further connected into vortex lines based on the mesh connectivities.



The movement of a vortex line is detected by checking each space-time edge to see whether it is intersected at an intermediate time between two adjacent frames. The punctured (space) faces and intersected (space-time) edges are further connected as vortex sheet graphs. Vortex lines in different frames are labeled with same IDs if they are connected by the same vortex sheet graph.

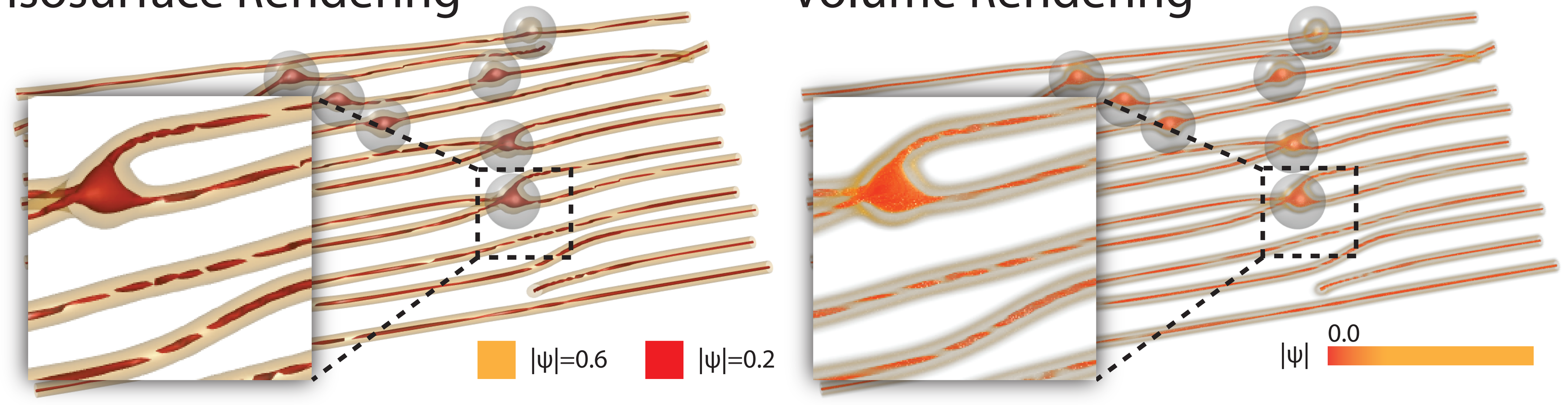


Events are detected if there are topological changes of vortex lines over time. Several event types are defined, including merge, split, birth, death, recombination, and other compound events. A storyline visualization is provided to show the events in the dataset.

Limitations of Traditional Visualization Methods

Isosurface Rendering

Volume Rendering



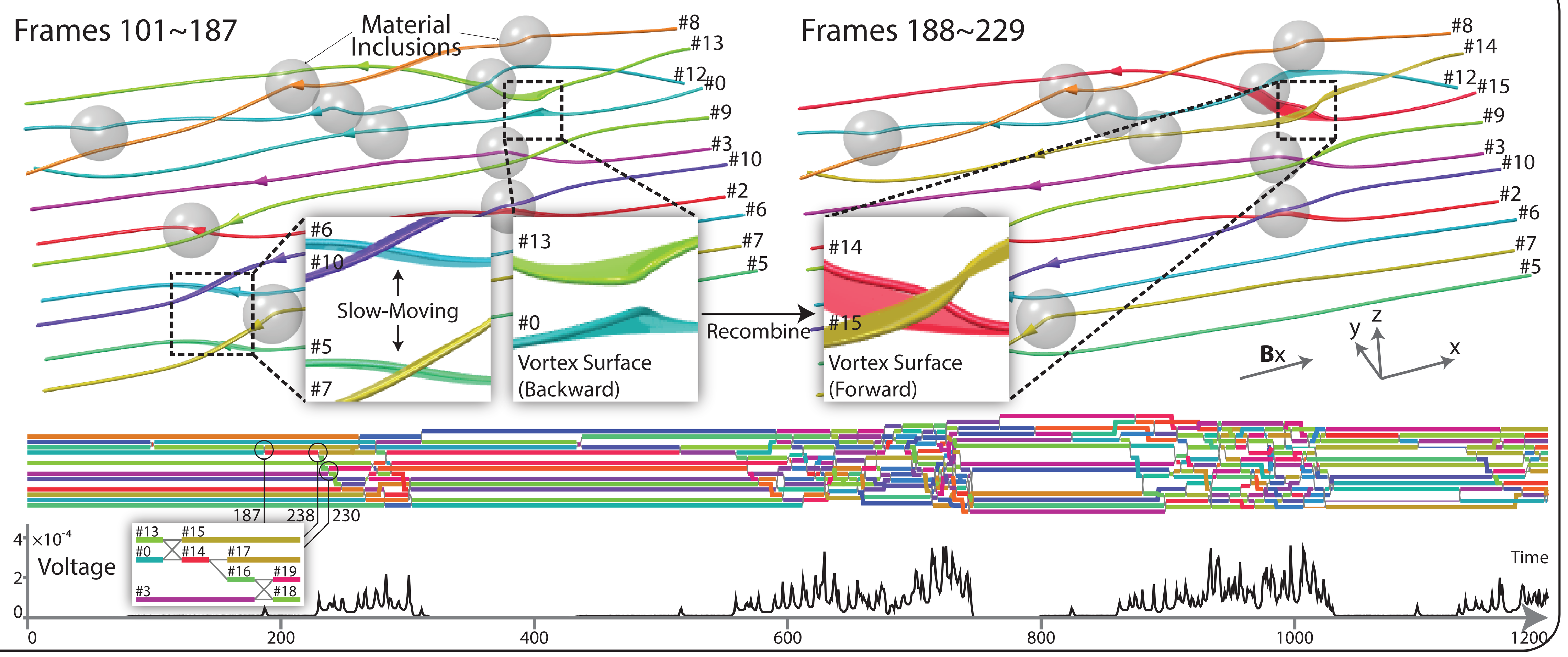
Traditional visualization techniques, such as isosurface rendering and volume rendering, usually blur the fine features of a vortex and merge when two vortices are in close proximity.

Results: 3D Structured Mesh Data

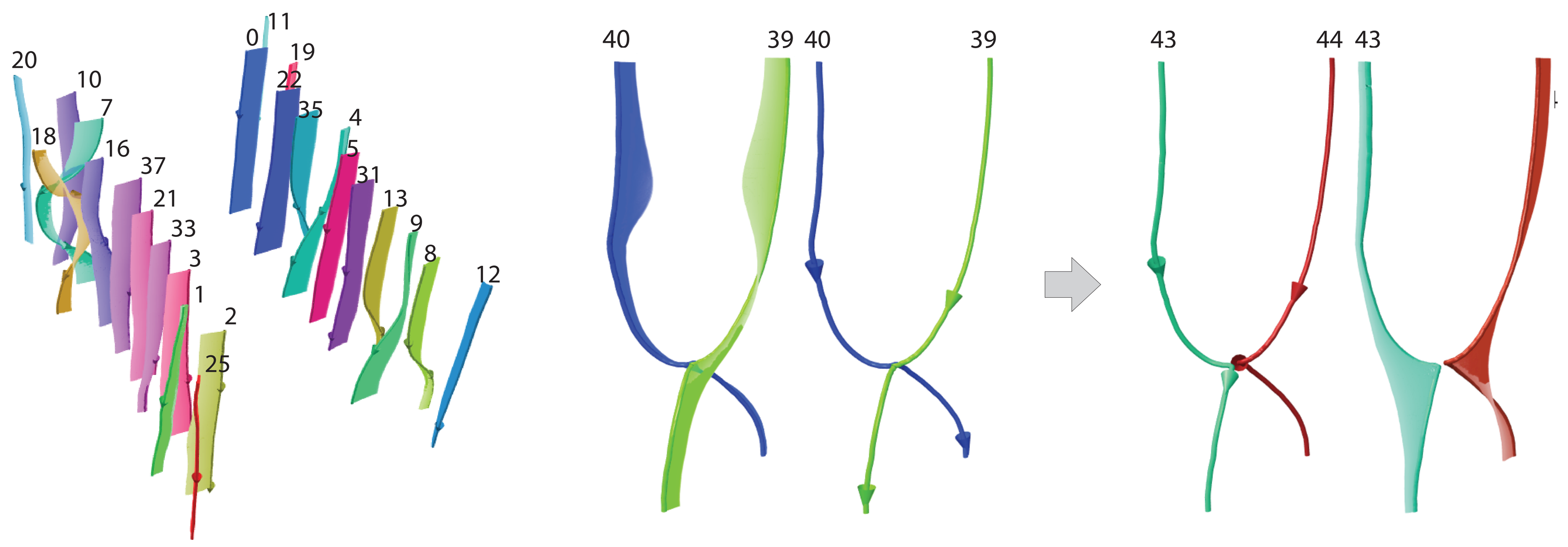
We visualize the vortex extraction and tracking results of a superconductor in a periodic dissipative state.

Top left: vortex surfaces (trajectories of vortex lines) from frame 101-187; **top right:** vortex surfaces from frame 188-299. Vortices #0 and #13 recombined and created two new vortices #14 and #15.

Bottom: the event visualization together with the voltage line chart. The correlation between vortex dynamics and energy dissipation can be observed.

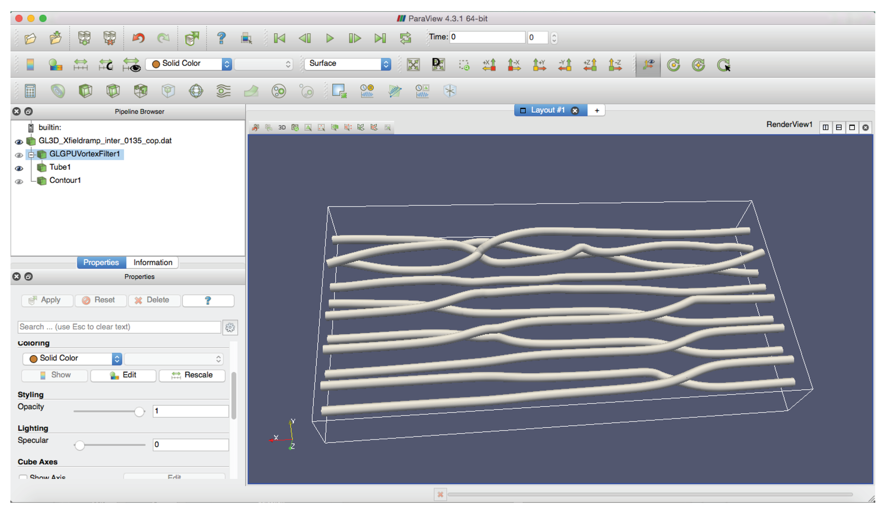


Results: 3D Unstructured Mesh Data



Left: vortex tracking results visualized with vortex surfaces;
Right: a vortex recombination event (vortices #39 and #40 swap parts to create new vortices #43 and #44). From the visualization, we can see how vortices deform before and after recombination.

Software Development and ParaView Plugins



A standalone visualization tool, as well as a ParaView plugin are developed for loading, analyzing, and visualizing TDGL simulation data.

The unstructured mesh data structures are based on libMesh, which is the finite element library used by the simulation. The framework can be integrated with the simulation for in-situ analysis in the future.

Publications

H. Guo, C. L. Phillips, T. Peterka, D. Karpeyev, and A. Glatz. Extracting, Tracking, and Visualizing Magnetic Flux Vortices in Complex-Valued Superconductor Simulation Data. *IEEE Transactions on Visualization and Computer Graphics (Proceedings of IEEE Scientific Visualization 2015)*, 21(12):-, 2015. (Accepted)

C. L. Phillips, T. Peterka, D. Karpeyev, and A. Glatz. Detecting Vortices in Superconductors: Extracting One-Dimensional Topological Singularities from a Discretized Complex Scalar Field. Physics Review E, 023331(91):1-12, 2015.

Acknowledgements

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